Introduction

1.1 Introduction

The optical fibers got attention for the communication system because of the tremendous bandwidth they offer (in the range of 10^{14} Hz). Dramatic improvement in the transmission characteristics of the optical fibers started the revolution in the field of optical fibers. It was indeed the development of the low-loss optical fibers (20 dB/km at He-Ne laser wavelength of 633 nm) in 1970 by Corning Glass Works in the United States that made possible the use of the optical fibers as a viable transmission medium in the lightwave communication system. Over the next several years, the optical fiber losses dropped dramatically, aided both by the improved fabrication methods and by the shift from an earlier wavelength to the longer wavelength where the optical fibers have inherently lower attenuation. The first generation of the telephone field trials in 1977 used such fibers to transmit light at 850 nanometer from the gallium-aluminum-arsenide laser diodes. Those first-generation systems could transmit the light several kilometers without repeaters, but were limited by the loss of approximately 2 dB/km in the fiber. A second generation soon appeared, using new InGaAsP lasers which emitted at 1300 nanometer, where the optical fiber attenuation was as small as 0.5 dB/km, and the pulse dispersion was nearly zero. Development of hardware for the first transatlantic fiber cable showed that single-mode systems were feasible to use and when deregulation opened the long-distance phone market in the early 1980s, the transmission systems of single-mode fiber with 1300-nm sources appeared. That technology had spread into other telecommunication applications and continues to remain as the standard for most fiber systems. However, a new generation of single-mode systems is now beginning to find applications in the submarine cables and systems serving large numbers of subscribers. They operate at a wavelength of 1550 nanometer, where the fiber loss varies from 0.2 to 0.3 dB/km, thereby allowing even longer repeater spacing. In addition to above, erbium-doped optical fibers can serve as the optical amplifiers at that wavelength, avoiding the need for the electro-optic regenerators. Submarine cables with optical amplifiers can operate at speeds to 5 gigabits per second, and can be simply upgraded from lower speeds to higher speeds by changing the terminal electronics. The optical amplifiers also are attractive for fiber systems delivering the same signals to many terminals, because the fiber amplifiers can compensate for losses in dividing the signals among many terminals [1-2]. The broadband communication emerges from the fact that instead of using one single wavelength laser to transmit information along the optical fiber, we can use the multiple wavelength lasers to transmit far more information along the same channel, thereby increasing the total capacity of the optical transmission. For example, using 48 distinct wavelength lasers, each modulated at 2.5 Gbps, represents an effective transmission rate of 48 times 2.5 Gbps, which is equal to 120 Gbps. If you can envision the future development of that modulation scheme, and technologies capable of achieving 10 Gbps, then the use of 100 distinct wavelength lasers could increase the effective data throughput to 1 Tbps. This idea appears to be moving toward reality, as many companies are providing the advanced WDM technologies that allow the service or the trunk providers to upgrade their system capacity in accordance with the ever-increasing demand for information [3].

The conventional single mode fiber (CSF) is characterized by a large (5-6 μm) core radii and zero dispersion occurs around 1300 nm. Operation around 1300 nm leads to a low pulse broadening with a low attenuation. But the lowest attenuation window for the silica fiber is at 1550 nm and thus, to exploit this low-loss window, the new fiber designs having the zero dispersion in the 1550 nm wavelength region are emerged. These fibers are referred to as Dispersion Shifted Fibers (DSF) and have typically a triangular refractive index profiled core. Using DSF operating at 1550 nm, one can achieve the zero dispersion as well as the minimum loss in the silica-based fibers [4].

Now, in many countries, tens of millions of kilometers of the CSF already exist in the underground ducts operating at 1300 nm. One could increase the transmission capacity by operating these fibers at 1550 nm and using the wavelength division multiplexing (WDM) techniques and optical amplifiers. But, then there comes a significant residual (positive) dispersion that will affect the transmission rate. On the other hand, replacing these fibers by the DSF would involve huge costs. As such, in recent years, there has been a considerable work in upgrading the installed 1300 nm optimized optical fiber links for the operation at 1550 nm. This is achieved by developing the fibers with a very large negative dispersion coefficient (over a few hundred meters to kilometers), which can be used to compensate for the dispersion over the tens of kilometers of the fiber in the link. These types of fibers are known as the *dispersion compensating fibers* (DCF) [5-10]. Since the DCF has to be added on to the existing fiber optic link, it will increase the total loss of the system and hence, will pose some problems in the detection at the end. Therefore, Er-doped optical fiber amplifiers (EDFA) are also employed along with the DCF in the link as shown in Fig. 1.

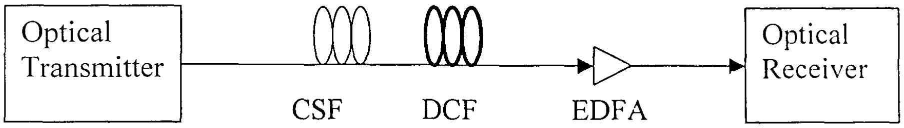

Fig. 1: A schematic of dispersion compensating scheme in a conventional single-mode fiber system operating at 1550 nm using the dispersion compensating fibers.

The passive DCF schemes can be broadly classified into the following categories:

(a) Higher-order mode DCF: Here, a higher-order mode instead of the fundamental mode is propagated in the fiber at preferably around cutoff wavelength and a large negative dispersion can be obtained. This is because near cutoff the propagation constant variation at the mode higher order than LP_{01} exhibits the more wavelength dependence and waveguide dispersion is the dominating factor and the dispersion of about −770 ps/km-nm has been reported in the literature [11-13]. The drawback with the higher-order mode DCF is that the mode converters are necessary to convert the fundamental modes into the higher-order mode and vice versa results in the increasing system cost as well as the insertion loss.

(b) Fiber Bragg gratings (FBG): They are also used successfully for the dispersion compensation [14-18]. The gratings used are the chirped gratings. Their compact size and the possibility of achieving dynamic dispersion compensation have attracted much attention to FBG for dispersion compensation.

(c) The DCF using the long period gratings (LPG): Since the transmission of the LPG varies with the length of the gratings or the refractive index modulations, it is shown that it is possible to tailor the transmission spectrum to obtain a high transmission with the constant dispersion and a negligible delay ripple over a small bandwidth [19]. However, the LPG and the FBG based DCF suffer from the drawbacks like the relatively small bandwidth, the ripples in the dispersion spectrum and a difficulty of mass fabrication.

(d) Dispersion compensation using a refractive-index profile modification: A novel DCF design capable of providing a very high dispersion value has been proposed for –5000 ps/km-nm dispersion [5] and the experimental realization is reported for –1800 ps/km-nm dispersion [6] and by the author for about –800 ps/km-nm at 1550 nm [7]. It consists of two highly asymmetric concentric cores and it has been shown that this design can provide a large value of dispersion with the proper choice of parameters. Based on the above, theoretical optimization of a dual core DCF for the DWDM transmission in the 1480-1610 nm band has been proposed [8] where the index profiles have been adjusted so as to get the mode field diameter match between the DCF and the CSF and also to achieve a high effective area to minimize the nonlinearities. Various authors have reported the design aspects of the DCFs and their realizations [21-24]. In the present scenario, it seems that DCF using profile modifications of the optical fiber is the popular choice for the passive dispersion compensation.

However, the attenuation offered by the DCF is quite larger (about 2 to 3 times) than that of the CSF and it needs an EDFA in the link. The splice loss penalty for the splice between the DCF and the EDFA is also a major thing to concern and hence, consideration of an Er-doped DCF (EDDCF) which can simultaneously perform the task of compensation for the dispersion as well as the signal amplification, thus, eliminating the need for an additional splicing while making the compensation unit more compact.

We have used the profile-modification method of dispersion compensation to fabricate the DCF. The Er-ions have been doped into the DCF so as to get simultaneous compensation of the dispersion as well as the losses.